

# MOLECULAR GAS IN NEARBY POWERFUL RADIO GALAXIES

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## Abstract

We report the detection of  $^{12}\text{CO}(1 \rightarrow 0)$  and  $^{12}\text{CO}(2 \rightarrow 1)$  emission from the central region of nearby 3CR radio galaxies ( $z < 0.03$ ). Out of 21 galaxies, 8 have been detected in, at least, one of the two CO transitions. The total molecular gas content is below  $10^9 M_{\odot}$ . Their individual CO emission exhibit, for 5 cases, a double-horned line profile that is characteristic of an inclined rotating disk with a central depression at the rising part of its rotation curve. The inferred disk or ring distributions of the molecular gas is consistent with the observed presence of dust disks or rings detected optically in the cores of the galaxies. We reason that if their gas originates from the mergers of two gas-rich disk galaxies, as has been invoked to explain the molecular gas in other radio galaxies, then these galaxies must have merged a long time ago (few Gyr or more) but their remnant elliptical galaxies only recently (last  $10^7$  years or less) become active radio galaxies. Instead, we argue the the cannibalism of gas-rich galaxies provide a simpler explanation for the origin of molecular gas in the elliptical hosts of radio galaxies (Lim et al. 2000). Given the transient nature of their observed disturbances, these galaxies probably become active in radio soon after the accretion event when sufficient molecular gas agglomerates in their nuclei.

## 1. Introduction

Bright radio sources served as the first signposts for highly energetic activity in galaxies. The nature of these galaxies, and the reason for their luminous radio activity, have since been subjects of detailed investigation. Although the vast majority resemble luminous elliptical galaxies, observations (Smith & Heckman 1989) showed that a significant fraction of the most powerful radio galaxies at low redshifts exhibit peculiar optical morphologies suggestive of close encounters or mergers between galaxies. Nevertheless, all of the powerful radio galaxies examined by Smith et al. (1990), mostly selected from the 3C catalog, lie within the fundamental plane of normal elliptical galaxies.

Some radio galaxies possess so much dust that they can be detected in the far-infrared by *IRAS*. This discovery has motivated many subsequent searches for molecular gas in radio galaxies, in all cases by selecting those with known appreciable amounts of dust. At low redshifts, eleven radio galaxies have so far been detected in  $^{12}\text{CO}$ . The detected galaxies span nearly three orders of magnitude in radio luminosity, and comprise those exhibiting core-dominated radio sources as well as classical double-lobed FR-I (edge darkened) and FR-II (edge brightened) radio sources. All have inferred molecular-gas masses between  $10^9 M_\odot$  and  $10^{11} M_\odot$ , except for the very nearby radio galaxy Centaurus A which has a molecular-gas mass of  $\sim 2 \times 10^8 M_\odot$  (Eckart et al. 1990). In four of the five cases the CO gas is found to be concentrated in a compact (diameter of a few kpc or smaller) ring or disk around the center of the galaxy. The molecular gas in radio galaxies may therefore comprise the reservoir for fueling their central supermassive black holes.

At low redshifts, the only other type of galaxy to commonly exhibit molecular gas masses as high as  $\geq 10^{10} M_\odot$  are infrared-luminous galaxies. These gas and dust rich galaxies exhibit vigorous star formation thought to be triggered by galaxy-galaxy interactions, and indeed the majority of ultraluminous infrared galaxies (i.e., those with  $L(60\mu\text{m}) \geq 10^{12} L_\odot$ ) are found to be merging systems of gas-rich disk galaxies. In the latter systems, the CO gas is found to be preferentially concentrated in a ring or disk around the nuclear regions of the merging galaxies (e.g Bryant & Scoville 1999). The observed similarities have prompted the suggestion that radio galaxies also originate from the mergers of two gas-rich disk galaxies, and in many cases comprise their still disturbed E/SO merger products (Mirabel et al. 1989, Evans et al. 1999a, 1999b).

Given the predisposition of the abovementioned surveys towards relatively dust-rich objects, are the radio galaxies so far detected biased towards those with unusually large amounts of molecular gas? It is not clear whether the IR-bright radio galaxies so far detected represent the most gas-rich members of a population that all possess substantial amounts of dust and gas, or extreme members of a population that possess a broad range of dust and gas masses. This issue is of importance for a proper understanding of the nature of radio galaxies, and what fuels their supermassive black holes.

To address this issue, we have initiated a deep survey of all the previously undetected radio galaxies at redshifts  $z \leq 0.031$  in the revised 3C catalog (Spinrad et al 1985). The objects in this catalog represent the most luminous radio galaxies at their particular redshifts in the northern hemisphere. At low redshifts the vast majority can be clearly seen to be luminous elliptical galaxies, which in most cases comprise first ranked galaxies in poor clusters of roughly ten members although a number reside in much richer environments (Zirbel 1997). Only a small minority have been detected in the infrared by *IRAS*; indeed, only three objects in this catalog have previously been detected in CO, one of which lies in the redshift range of our survey.

## 2. Molecular gas

Out of the 21 sources observed, 8 have been detected in  $^{12}\text{CO}(1 \rightarrow 0)$  and 3 in  $^{12}\text{CO}(2 \rightarrow 1)$  (see Table 1). The line profiles of the  $^{12}\text{CO}(1 \rightarrow 0)$  and  $^{12}\text{CO}(2 \rightarrow 1)$  emission are shown in Fig. 1. Because of the half-power beam of the IRAM-30m, we are mainly sensitive to emission from the central part of the radio-galaxies, typically the inner 10/5 kpc for the  $(1 \rightarrow 0)/(2 \rightarrow 1)$  transitions. We emphasize nevertheless that the CO beam sizes are larger than the dust features seen in these radio-galaxies (Martel et al. 1999).

The double-horned line profile is clearly observed in 5 radio-galaxies and is characteristic of an inclined rotating disk with a central depression in CO emission at the rising part of its rotation curve (Wiklind et al. 1997). The rotational velocities observed are quite high and if they are corrected for the inclination of the dust disk they reach high values which are more typical of the nuclear molecular-gas disks or rings in IR-luminous galaxies. Using a standard CO-to- $\text{H}_2$  conversion factor we estimate the molecular content (see Table 1) within these galaxies. In the case of 3C253, where we have only a detection in  $^{12}\text{CO}(2 \rightarrow 1)$ , we compute the molecular mass using the mean average line ratio.

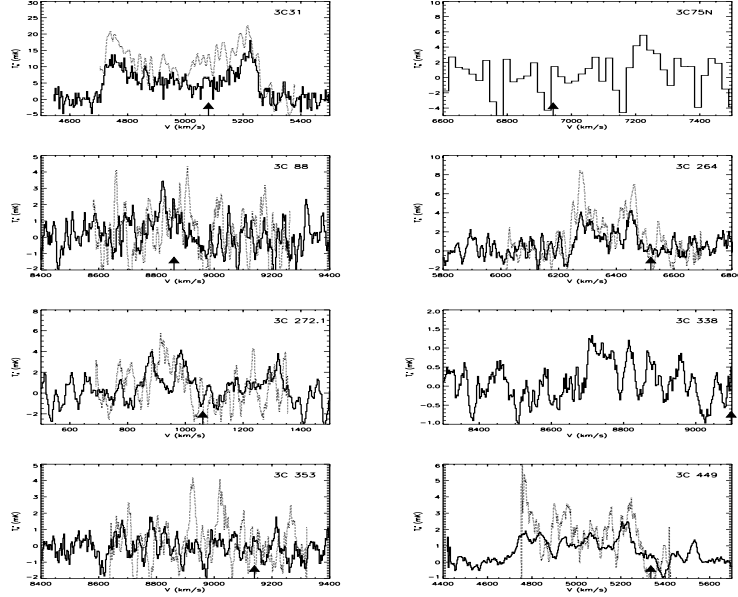


Figure 1. CO(1-0) spectra (solid line) with CO(2-1) spectra (dotted line) towards a sample of 3CR radio galaxies detected in, at least, one of the both transition lines. The vertical arrows show the optical velocity.

The line ratio of  $^{12}\text{CO}(2 \rightarrow 1)/^{12}\text{CO}(1 \rightarrow 0)$ , with the individual line intensities measured provides information on the opacity and excitation of the gas. Line ratio less than 0.7 imply that the gas has different filling factor in the two transitions or is subthermally excited, whereas line ratio greater than unity imply that the gas is optically thin. If both transitions originate from a region comparable in size with their individual dust features, as is the case in all the galaxies so far mapped in CO, the line ratios are between 0.6 and 0.8. These values are close to the extreme upper limits measured for many inactive elliptical galaxies (Wiklind et al. 1995), but close to the average value of 0.9 measure at the centers of both inactive and active disk galaxies (Braine & Combes 1992).

### 3. Discussion

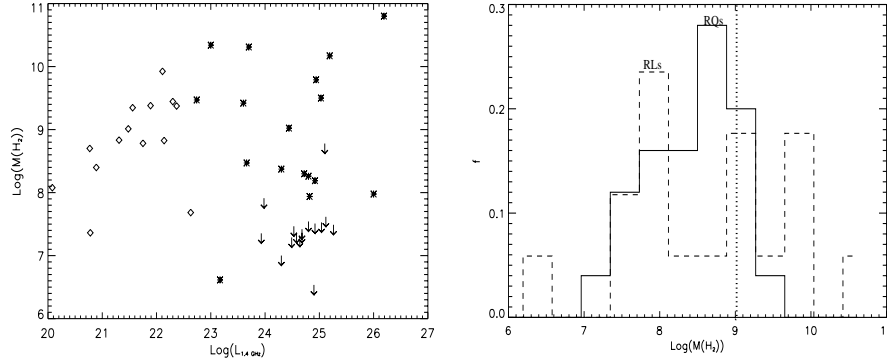
The total/upper-limit molecular mass found in this 3CR sample of radio galaxies is well below the molecular mass found in a typical galaxy like the Milky Way (several  $10^9 M_\odot$ ) for most of the case. We detected only  $4 \times 10^6 M_\odot$  molecular gas in the nearby radio-galaxy 3C272.1 (M84) and an upper-limit of  $3.4 \times 10^6$  in 3C270 (M87). These low val-

Name	Velocity (km.s <sup>-1</sup> )	Transition	I(CO) (K.km.s <sup>-1</sup> )	M(H <sub>2</sub> ) (Log(M <sub>⊙</sub> ))
3C31	5071	<sup>12</sup> CO (1 → 0)	3.87	9.02
		<sup>12</sup> CO (2 → 1)	4.80	
3C75N	6816	<sup>12</sup> CO (1 → 0)	0.37	8.26
3C88	8859	<sup>12</sup> CO (1 → 0)	0.18	8.19
3C264	6523	<sup>12</sup> CO (1 → 0)	0.45	8.30
		<sup>12</sup> CO (2 → 1)	0.93	
3C272.1	1060	<sup>12</sup> CO (1 → 0)	0.35	6.61
		<sup>12</sup> CO (2 → 1)	0.77	
3C338	9100	<sup>12</sup> CO (1 → 0)	0.10	7.94
3C353	9150	<sup>12</sup> CO (2 → 1)	0.20	7.98
3C449	5345	<sup>12</sup> CO (1 → 0)	0.86	8.37

Table 1. Radio-galaxies detected in <sup>12</sup>CO transitions in our survey.

ues contrast with the previous high-content molecular gas found mainly in IRAS-selected radio-galaxies (Mazzarella et al. 1993, Evans et al. 1999a,b). On the Fig. 2 the distribution of the molecular gas mass in the radio galaxies show the dichotomy between the IRAS-selected sample of radio-galaxies and our 3C sample: a clear cut appears at 10<sup>9</sup>M<sub>⊙</sub> between both samples. Compared to a sample of radio-quiet elliptical galaxies (Knapp & Rupen 1996, Wiklind et al. 1997) the 3C sample exhibits a statistically significant lower gas mass content than the elliptical galaxy sample.

A possible link between Ultra-Luminous Infrared Galaxies (ULIRGs) and radio-galaxies has been proposed (Evans et al. 1999b). Some case exhibits properties that place them in both categories. The question is if major mergers are responsible for the AGN phase in radio galaxies. By comparison with ULIRGs, however, radio galaxies exhibit a much broader range of molecular gas masses. Moreover the host galaxies of the 3C sample appear to be very well relaxed and lie in the fundamental plane. The timescale for relaxation after a merging is about 1-2 Gy. Nevertheless the radio emission phase is *very short*, few 10<sup>7</sup> years. Given the accretion rate for the AGN (< 1 M<sub>⊙</sub>.yr<sup>-1</sup>), only few massive GMCs (10<sup>6</sup>M<sub>⊙</sub>) would be sufficient to fuel the AGN. Indeed in the nearby radio galaxies (M84, M87) observed, the detection or upper-limit of molecular gas are lower than 10<sup>7</sup> M<sub>⊙</sub>. In our survey only low molecular gas content has been detected. Major mergers require radio galaxies to be very old merger remnants that have only recently become active after the remnant has relaxed and much of the gas disappeared. But minor mergers present a simpler alternative to the dust and molecular gas seen in many 3CR radio galaxies. Furthermore they can explain the presence



*Figure 2.* Left: Molecular gas content vs. radiocontinuum (1.4 GHz). Right: Histogram of the molecular content in the radio-galaxies (RGs) and elliptical radio-quiet. The vertical dash line is at the maximum molecular gas mass detected in our 3CR sample. galaxies (RQs).

of a molecular disk and the loss of angular momentum necessary to bring the gas towards the center.

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